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Dilepton Transverse Momentum in the Color Dipole Approach¹

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Abstract

We investigate the Drell-Yan transverse momentum distribution in the framework of the color dipole approach. Special attention is paid to parton saturation effects at high energies. Predictions at LHC energies ($\sqrt{s} = 14$ TeV) are given and extrapolated down to ISR energies ($\sqrt{s} = 62$ GeV). Unitarity corrections are implemented through the multiple scattering Glauber-Mueller approach and are compared with predictions of the BGBK saturation model.

1 Introduction

The high energies available in hadronic collisions at RHIC and to be reached at LHC will provide new information on parton saturation and nuclear phenomena. In these kinematical domains, massive lepton pairs production in hadronic collisions (Drell-Yan process [1]) can be used as a clean signal to investigate the high parton density regime.

In the color dipole approach, the Drell-Yan (DY) process is viewed in the rest frame of the target, where it looks like bremsstrahlung of a virtual photon decaying into a lepton pair [2], rather than parton annihilation. The DY cross

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section can then be expressed in terms of the dipole cross section extracted from small- x Deep Inelastic Scattering (DIS). Although the mechanism of dilepton production appears to be quite different in the dipole formulation from what one is used to in the parton model, at low x , the equivalence between both approaches has been demonstrated numerically [3] and analytically [4]. The advantage of the dipole formulation is that it allows for an easy implementation of saturation effects, which avoid the divergence of the DY cross section at low transverse momentum ($p_T \rightarrow 0$). (in contrast to the result in the infinite momentum frame)

In the following we report the main results on Ref. [4], where we investigated the DY dilepton transverse momentum distribution with regards to unitarity (parton saturation) aspects, which play an important role at high energies. These effects are included into the dipole cross section through the multiple scattering Glauber-Mueller approach [5]. Results are compared to predictions from the QCD improved saturation model of Ref. [6].

2 The Drell-Yan cross section in the color dipole approach

In terms of color dipole degrees of freedom, the differential cross section for radiation of a virtual photon with mass M from a quark (or an antiquark) scattering on a proton reads [7],

$$\begin{aligned} & \frac{d\sigma(qp \rightarrow \gamma^* X)}{d \ln \alpha d^2 p_T} \\ &= \frac{1}{(2\pi)^2} \int d^2 r_{\perp 1} d^2 r_{\perp 2} e^{i \vec{p}_T \cdot (\vec{r}_{\perp 1} - \vec{r}_{\perp 2})} \Psi_{\gamma^* q}^{*T,L}(\alpha, \vec{r}_{\perp 1}) \Psi_{\gamma^* q}^{T,L}(\alpha, \vec{r}_{\perp 2}) \\ & \times \frac{1}{2} \left\{ \sigma_{dip}(x_2, \alpha r_{\perp 1}) + \sigma_{dip}(x_2, \alpha r_{\perp 2}) - \sigma_{dip}(x_2, \alpha(\vec{r}_{\perp 1} - \vec{r}_{\perp 2})) \right\}, \quad (1) \end{aligned}$$

where α is the light-cone momentum fraction that the γ^* takes from its parent quark and $r_{\perp i}$ is related to the γ^* -quark transverse separation [7]. Explicit expressions for the light-cone wavefunctions $\Psi_{\gamma^* q}^{T,L}$ can be found *e.g.* in Ref. [3]. The measured cross section is obtained by embedding Eq. (1) in the hadronic environment, observing that the projectile quark carries momentum fraction

$x = x_1/\alpha$ of the parent hadron. Correspondingly, x_1 is the momentum fraction of the proton carried by the photon.²

The cross section for a small color dipole scattering off a nucleon can be obtained from perturbative QCD. However, there is a large uncertainty coming from non-perturbative aspects (infrared region) of the scattering and higher orders associated with a perturbative expansion (higher twists). A close connection with the DGLAP parton densities can be obtained in the double logarithmic approximation. In that limit, the dipole cross section can be written as,

$$\sigma_{dip}(x, r_\perp) = \frac{\pi^2 \alpha_s}{3} r_\perp^2 x G^{\text{DGLAP}}(x, \tilde{Q}^2), \quad (2)$$

where $xG^{\text{DGLAP}}(x, \tilde{Q}^2)$ is the usual DGLAP gluon distribution at momentum fraction x and virtuality scale $\tilde{Q}^2 = 4/r_\perp^2$ [8]. Concerning the non-perturbative contribution, our procedure is to freeze the dipole cross section in a suitable scale larger than r_{cut}^2 , which corresponds to the initial scale on the gluon density perturbative evolution $Q_0^2 = 4/r_{\text{cut}}^2$. At high energies, an additional requirement should be obeyed. The growth of the partons density (mostly gluons) has to be tamed, since an uncontrolled increasing would violate the Froissart-Martin bound. Then, the black disc limit of the target has to be reached at quite small Bjorken x . We implement this requirement by using the multiple scattering Glauber-Mueller approach, which slows down the growth of the gluon distribution in an eikonal way in the impact parameter space [5]. Therefore, we substitute xG^{DGLAP} in Eq. (2) by the corrected distribution that also includes unitarity effects (see Ref. [8] for further details).

The color dipole picture is only valid at small x_2 , and it takes into account only sea quarks produced from gluon splitting in the target, neglecting its valence content. (However, both valence and sea quarks distributions are parameterized in the projectile structure function.) At lower energies, x_2 increases and non-gluonic (valence) contributions to the process are not negligible. In order to extend the dipole approach down to lower energies, we make use the following educated guess. The dipole cross section, Eq. (2), represents the asymptotic gluonic (Pomeron) contribution to the process. At larger x , however, a non-asymptotic quark-like content should also be included. In Regge language, this

²We use standard kinematical variables, $x_1 - x_2 = x_F$ and $x_1 x_2 = (M^2 + q_T^2)/s$.

contribution corresponds to a Reggeon instead of a Pomeron exchange in the t -channel [8]. Hence, we add a Reggeon contribution to the dipole cross section, Eq. (2), which is parametrized in a simple way, $\sigma_{dip}^R = \sigma_0 r_\perp^2 x q_{\text{val}}(x, \tilde{Q}^2)$. With a value of $\sigma_0 = 7$, we obtain a reasonable description of the DY mass distribution measured by E772. Similar results were obtained in Ref. [8]. The quantity q_{val} is the valence quark distribution from the target, evolved through DGLAP.

A quite successful phenomenological realization of the parton saturation phenomenon is rendered by the QCD improved saturation model of Ref. [6]. This model reproduces the DGLAP evolution for small dipoles and the black disk limit down to small virtualities (large dipoles) in the eikonal form,

$$\sigma_{dip}(x, r_\perp) = \sigma_0 \left\{ 1 - \exp \left(-\frac{\pi^2 r_\perp^2 \alpha_s(\mu^2) x g(x, \mu^2)}{3\sigma_0} \right) \right\}. \quad (3)$$

Here, $g(x, \mu^2)$ is the gluon density of the target, DGLAP evolved to the scale μ^2 , which is assumed to have the form $\mu^2 = \frac{C}{r_\perp^2} + \mu_0^2$. All free parameters have been taken from the Ref. [6]. In the following we compare the saturation model with the results coming from the Glauber-Mueller approach.

3 Results and Conclusions

We calculate the DY p_T distribution in proton-proton (pp) collisions at LHC energy ($\sqrt{s} = 14$ TeV). In addition, we evaluate the x_F -integrated cross section at ISR energy ($\sqrt{s} = 62$ GeV) and compare it with available DY data (from pp scattering) in the mass interval $5 \leq M \leq 8$ GeV [9]. Our results are shown in Fig. 1. The solid line in the Fig. 1:(a) denotes the result using the GM distribution, whereas the dashed line was obtained with the GRV94 gluon parametrization, *i.e.* without saturation. The dot-dashed line labels the result using GRV98. The aim of this comparison is to find out to what extent an updated parametrization could absorb unitarity effects in the fitting procedure. We conclude that at LHC energy, those effects could not be absorbed in a new parametrization. As an additional comparison, we present curves from the improved saturation model BGBK [6] (dotted lines). In Fig. 1:(b) the solid curve denotes the Glauber-Mueller calculation, including the non-asymptotic valence content (GM + Reggeon) and the dot-dashed line represents the BGBK

calculations. Both results are in reasonable agreement with shape and overall normalization of the data. In order to discriminate among saturation models, one needs measurements at high energy accelerators such as RHIC and/or LHC, preferably in the large rapidity region.

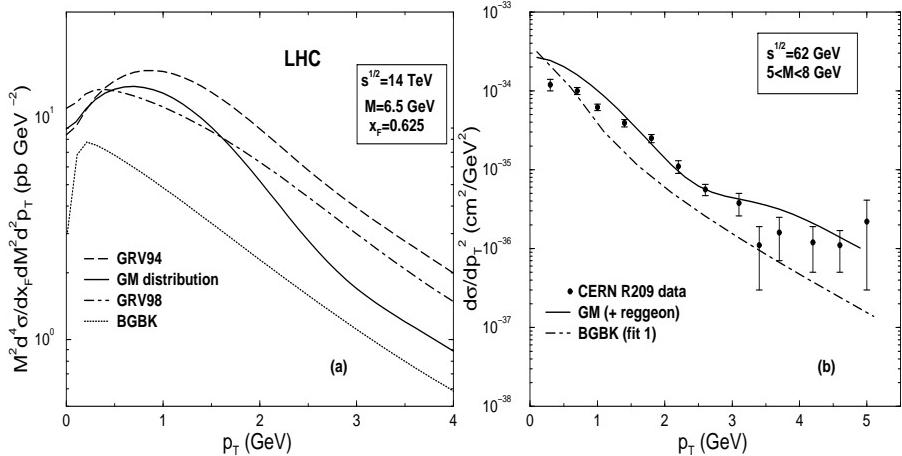


Figure 1: The Drell-Yan p_T distribution at (a) LHC energies (b) and CERN R209 energies $\sqrt{s} = 62$ GeV.

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